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Key Points:

- A linear dune was monitored over an 8 year period
- The linear dune has mainly accreted vertically with little linear extension
- These observations support global circulation models for Titan

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Temporal observations of a linear sand dune in the Simpson Desert, central Australia: Testing models for dune formation on planetary surfaces

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Abstract Linear dunes are the most common dune form found on planetary surfaces, yet questions remain about their formation. Temporal observations of a linear dune located in the Simpson Desert of central Australia were made to monitor dune movement and to test competing hypotheses regarding linear dune formation. Our observations were collected on three separate occasions from 2006 to 2014. Rebar stakes were placed in a gridded pattern so that multiple measurements of sand thickness, GPS surveys, and photographs could be taken at the same locations over time. We observed widespread reworking of sand on and around the dune crest, with sand accumulation locally exceeding a meter between surveys. Overall, the height of the dune crest increased by several centimeters. We also observed fluctuations in the sand cover in the adjacent swales that often exceeded 2–3 cm between surveys, yet we did not observe any appreciable changes in the position of the dune's downwind terminus. Weather data indicate that the effective sand-transporting winds in the Simpson are widely unimodal. Net sediment flux (resultant drift direction) is toward the north-northwest, locally at an oblique angle to dune orientation. Collectively, our results suggest that the linear dune is actively maintained by vertical accretion. The implications from our observations are that linear dunes on other planetary surfaces could form in wind regimes that are widely unimodal, even where the resultant drift direction is locally oblique to dune orientation. In particular, such findings may provide support for global circulation models of Titan.

1. Introduction

Linear dunes (sometimes referred to as longitudinal dunes) are common aeolian landforms and represent ~40% of all dunes found on Earth [*Lancaster*, 1982; *Bristow et al.*, 2000]. These dunes are also found on all the planets and moons that have an appreciable atmosphere, having been observed on Titan, Venus, and Mars [*Edgett and Blumberg*, 1994; *Lee and Thomas*, 1995; *Lorenz et al.*, 2006; *Bourke et al.*, 2010; *Craddock*, 2012]. Linear dunes can be a few tens of meters to several hundred meters wide, and their lengths commonly reach many tens to hundreds of kilometers with crestlines that are straight to irregularly sinuous. On Earth, linear dunes form in hyperarid, arid, and semiarid regions, typically in moderately variable or bimodal regional wind speeds and directions where there is moderate sand supply [*Wasson and Hyde*, 1983]. Yet despite their common occurrence, there is still considerable debate over how linear dunes form.

Part of the reason why a unique solution does not exist for the formation of linear dunes is because these features represent some of the largest dune forms on any planet or moon. It is difficult, for example, to place constraints on the age, composition, and stratigraphy of a large linear dune over its entire length, especially when this reaches tens or hundreds of kilometers. What is beginning to emerge from ground-penetrating radar [*Bristow et al.*, 2000, 2007b] and luminescence dating [*Munyikwa et al.*, 2000; *Hollands et al.*, 2006; *Tefler*, 2011; *Hesse*, 2014] studies is that many large linear dunes probably represent composite structures that have formed over multiple episodes of aeolian activity. Complicated internal stratigraphy [e.g., see *Munyikwa*, 2005] makes it difficult to relate linear dune formation to specific past climates (e.g., rainfall or wind regimes). Nonetheless, the preservation of stratigraphy and interpretation of the climatic changes they record do depend in part on the wind regimes where the linear dunes formed, and a variety of wind regimes have been proposed, including helical roll vortices [e.g., *Tseo*, 1993], unimodal winds [*Fryberger*, 1979; *Tsoar*, 1989], and bidirectional winds [*Lancaster*, 1982; *Tsoar*, 1983; *Parteli et al.*, 2009]. In places such as central Australia and the

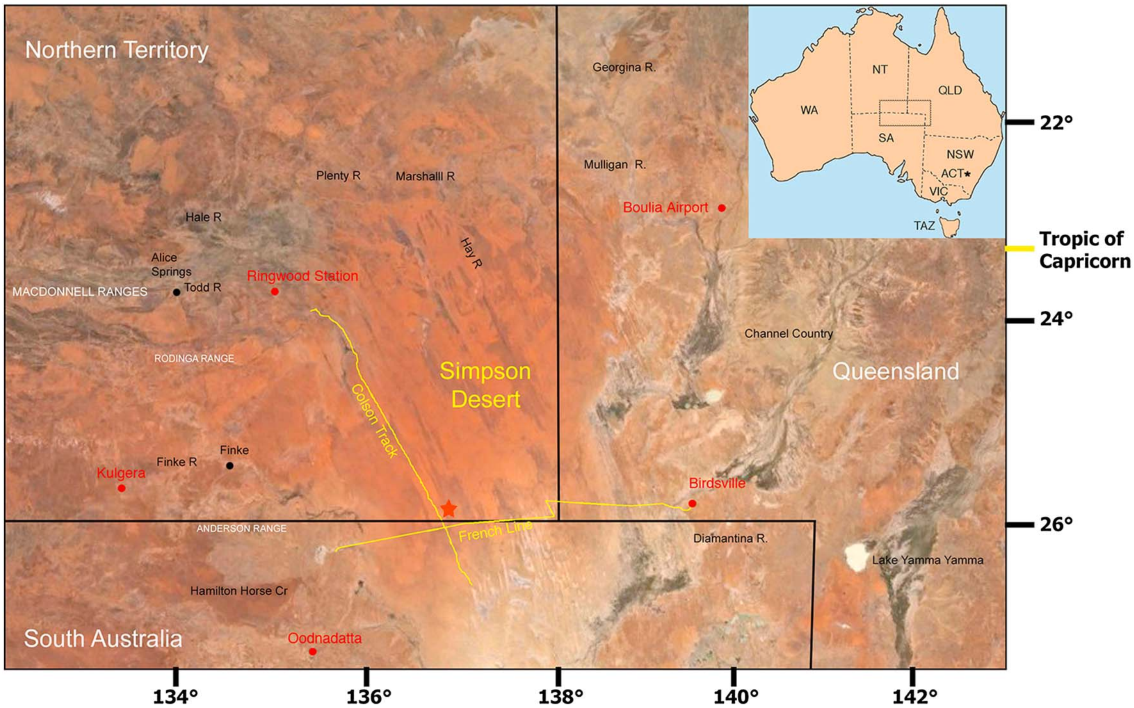

Figure 1. Map showing the Simpson Desert and surroundings. The Simpson lies on the borders of the Northern Territory, South Australia, and Queensland (inset). The weather stations where wind data were recorded (Table 2) are shown with red dots. Yellow lines show the French Line and Colson Track, and a red star marks the location of the field site (*image from Google Earth*).

Kalahari, the difficulty of placing ages and climatic constraints on linear dune formation is complicated further by vegetation, other forms of bioturbation and a variety of degradational processes, which may have perturbed the upper meter or more of sand [*McFarlane et al*., 2005; *Bristow et al*., 2007b]. In addition, and with only some exceptions [*Hesp et al*., 1989; *Tseo*, 1990; *Rubin et al*., 2008; *Zhang et al*., 2010], few studies have attempted to monitor changes in a linear dune over time. Consequently, additional research is needed to understand their dynamics and to provide constraints on their physical properties (e.g., grain size and stratigraphy). All these types of observations are necessary for a comprehensive understanding of the nature of linear dunes, not only on Earth but also on other planets and moons.

Dune monitoring studies provide a unique opportunity to decipher linear dune formation mechanisms and may provide key insights into the possible surface processes leading to linear dune formation on other planetary surfaces. Here, we present results of a monitoring study of a single linear dune located in the Simpson Desert in central Australia (Figure 1). Our observations were collected during three field campaigns over an 8 year period where the timing was dictated primarily by funding limitations. The dune was selected for monitoring based on its remote yet accessible location as well as the presence of a distinctive downwind terminus ("snout"), which allowed us to test competing theories for linear dune formation. The purpose of our study was to monitor and quantify linear dune changes over time and to test the relative importance of the different models proposed for linear dune formation, including linear extension [*Tsoar*, 1989; *Telfer*, 2011], vertical accretion (i.e., "wind rift") [*King*, 1960; *Pell et al*., 1999, 2000; *Hollands et al*., 2006], and lateral migration [*Hesp et al*., 1989; *Rubin*, 1990; *Nanson et al*., 1992; *Bristow et al*., 2007a]. Although this study represents observations of a single dune over a short interval of geologic time, the results nonetheless can provide insight into the dynamics of linear dunes on Earth that can help decipher surface processes leading to linear dune formation on other planets and moons.

2. Background

2.1. The Simpson Desert

The Simpson Desert in central Australia covers a vast area of ~170,000 km^2, occurring primarily within the Northern Territory and extending into western Queensland and the northern portion of the state of South

Australia Territories (Figure 1). Originally known as the Arunta Desert and referred to as "Australia's dead heart" in literature [*Madigan*, 1946], it is dominated by northwest to north-northwest oriented parallel linear dunes that typically range from 10 to 40 m in height and may be up to several hundred kilometers in length [e.g., *Twidale and Wopfner*, 1990]. Interdune spacing is typically between 100 m and 1.5 km and tends to vary as a function of dune height [*Twidale and Wopfner*, 1990]. Because the Simpson Desert was one of the last of the world's great deserts to be explored by westerners [see *Madigan*, 1946], our understanding of the chronology of the sand emplacement and associated dune formation is rapidly changing. Initial thermoluminescence (TL) dating of sand grains within the core of dunes indicated that some of the dunes may have been emplaced as early as ~100 ka years ago [e.g., *Nanson et al*., 1992], but more recent cosmogenic isotope dating has extended the age range back in time and shown that the Simpson dune field may have started to form as early as the middle Pleistocene (~1 Mya) [*Fujioka et al*., 2009]. Complementary optically stimulated luminescence (OSL) dating shows that many linear dunes may have persisted since this time but that the dune bodies have undergone many periods of extensive reworking and pedogenesis, leading to complex internal stratigraphies [*Fujioka et al*., 2009].

Based on the physical and chemical characteristics of the sand, including color, grain size, heavy minerals, quartz oxygen isotope composition, and zircon U-Pb ages, *Pell et al*. [1999] determined that the Simpson Desert is composed of at least two principal sand deposits or "groups" that are restricted to particular regions. The characteristics of the sand group located in the southeastern Simpson Desert, and the neighboring Tirari and Strzelecki deserts, suggest it was derived from the deflation of flood flats associated with major rivers and salt lake systems [*Pell et al*., 1999]. The characteristics of the sand group in the northern and western regions of the Simpson Desert suggest it was derived from underlying sediments that had undergone significant weathering and erosion [*Pell et al*., 1999]. Based on zircon ages, *Pell et al*. [1999] suggest that the source of the sand may have been multiple protoliths that were located hundreds of kilometers away. This suggests that most of the sand forming the Simpson Desert dunes was originally transported into the region by ancient fluvial processes [*Pell et al*., 1999; *Craddock et al*., 2010].

Originally, the average thickness of the sand cover in the Simpson Desert was thought to be ~1 m thick based on an estimate by *Wilson* [1973] that used crude topographic measurements of dune heights while assuming that the dunes lie directly on the basement geology. Basically, *Wilson* [1973] estimated the volume of sand contained in the linear dunes themselves and then determined the thickness of the sand cover simply by dividing by the surface area of the Simpson Desert. Although some dunes that are located near the margin of the desert do lie on bedrock, a majority of the dunes are located on a sand cover that extends to considerable depths. Borehole data indicate that this sand cover is actually ~10–35 m thick throughout much of the desert [e.g., *Wopfner and Twidale*, 1967]. Although the cross-sectional geology varies and locally the sand cover is interbedded with Tertiary fluvial or lacustrine sediments, the sand cover typically sits unconformably on shale and siltstones from the Late Cretaceous Winton and Mackunda Formations [*Wopfner and Twidale*, 1967; *Wells et al*., 1968; *Smith et al*., 1963; *Mond*, 1973; *Joklik et al*., 1985; *Craddock et al*., 2010].

2.2. Proposed Models for Linear Dune Formation

Linear dunes are often described using *Tsoar's* [1989] classification system that recognizes two types of dunes with longitudinal morphology. The first types are dunes that consist of a simple, longitudinal pattern which are either vegetated or unvegetated. *Tsoar* [1989] refers to the former as "vegetated linear dunes (VLDs)" that are characterized by their rounded crests, while the latter are called "seif" ("sword" in Arabic) dunes owing to their sharp, sinuous crests. The other types are lee dunes that have a longitudinal shape with a sharp-edged crest similar to a seif dune. Lee dunes form from sand accumulating in the lee side of obstacles such as plants, boulders, or cliffs. The linear dunes in Australia, including the Simpson Desert, are classified as VLDs in this system. Seif dunes are common in the Sahara and parts of the Middle East [*Tsoar*, 1989, 2014]. Lee dunes have been proposed for Mars [*Schatz et al*., 2006] and have been identified recently in China [*Rubin and Hesp*, 2009].

2.2.1. Linear Extension Model

The classic model is that linear dunes form where there is loose sand and winds blow from an oblique, bimodal direction or, alternatively, a unimodal direction so that the dune advances forward [e.g., *Tsoar*, 1989]. In this "linear extension" model, sand is derived from a single source upwind of the dune field and is transported over great distances down the long axis so the linear dunes grow forward [e.g., *Twidale and Wopfner*, 1990; *Wopfner and Twidale*, 2001]. The sand located in the swales is either deflated from existing dunes or has not yet been incorporated into a dune.

The parallel and regular spacing of linear dunes has also led to suggestions that parallel helical roll vortices contribute to their linear extension. First proposed by *Bagnold* [1953], temperature differences between the dune crests and swales are thought to generate a pressure gradient that imparts a spiral spin to the local airflow [*Glennie*, 1970]. The spiral flow advances down the swale and transports sand from the swales up the dune flanks. Such a wind regime for the formation of linear dunes seems implausible for a number of reasons. For example, in many places (including the Simpson), the spacing between linear dunes is commonly much smaller than the dimensions of any reported helical roll vortices [*Breed and Grow*, 1979]. Also, because the dunes themselves are involved in generating the pressure gradients to drive the helical rolls, such wind regimes do not explain how the dunes formed in the first place.

2.2.2. Vertical Accretion/Wind Rift

In the "wind rift" model, first proposed by *King* [1960], sand is transported up the flanks of the linear dunes so that they accrete vertically and uniformly along their entire lengths. *King* [1960] also suggests that the sand is derived locally and is not transported any great distances. Support for this model comes from detailed analyses of the characteristics and provenances of sand located in multiple Australian deserts, [*Pell et al*., 1999, 2000] where it has been suggested that linear dune formation occurs from "lateral sand migration and upward growth" [*Pell et al*., 2000] and little evidence has been found for significant downwind migration of the sand. Luminescence dating (TL and OSL) also provides support for the dominantly vertical growth of many linear dunes in the Simpson Desert [e.g., *Hollands et al*., 2006].

2.2.3. Lateral Migration

Several studies have suggested that linear dunes can move sideways [e.g., *Hesp et al*., 1989; *Rubin*, 1990; *Nanson et al*., 1992; *Rubin et al*., 2008], findings confirmed by more recent ground-penetrating radar studies of linear dunes in the Camel Flat basin within the Simpson Desert [*Hollands et al*., 2006] and in the Namib Desert [*Bristow et al*., 2007a]. We refer to this as the "lateral migration" model. These studies show that the crests of many linear dunes are laterally offset from their more clay-rich cores. While *Bristow et al*. [2007a] and *Hollands et al*. [2006] support the idea that linear dunes accrete vertically, they also suggest that instead of growing uniformly along the long axis of the dune, sand accumulates preferentially along one side of the dune, causing them also to migrate laterally over time. This may result in smaller dunes eventually coalescing into larger ones, which could explain why larger, taller dunes are found in the eastern Simpson Desert [*Twidale and Wopfner*, 1990].

2.3. Field Monitoring Objective

Collectively, these previous studies may suggest that there may be three different components to linear dune dynamics: linear extension, vertical accretion, and lateral migration. Given the immense size of most linear dunes, the lack of primary sedimentary structures within the dunes due to bioturbation, other disturbances, and illuviation [*Bristow et al*., 2007a], and the difficulty in establishing dune chronologies, it is also probable that linear dune formation is much more complicated than any single model suggests. The consensus that is beginning to emerge is that linear dunes are composite features and that the relative importance of linear extension, vertical accretion, and lateral migration may actually change over time [*Hollands et al*., 2006; *Bristow et al*., 2007a, 2007b; *Telfer*, 2011]. The purpose of our field monitoring was to observe changes in a linear dune over time to help constrain the relative importance of the different formation models in the present-day Simpson Desert and, by analogy, other planetary surfaces as well.

3. Methods

The primary access into the Simpson Desert is through an east-west trending, four-wheel drive road known as the French Line, which was established in the 1950s by a French petroleum company contracted by the Australian government to assess oil reserves (Figure 1). Today, it is maintained exclusively by occasional vehicle traffic. Off the French Line is the north-south trending Colson Track that receives noticeably less vehicle traffic and may even disappear under wind-blown sediment from lack of use. The dune we selected for monitoring is located approximately 32 km north of the French Line along the Colson Track (Figure 1). We chose this dune not only for its remote location, which is free from human influences or cattle disturbance, but also because of its distinctive snout. The snout is important because if linear dunes form as the result of linear extension, then sediment should preferentially accumulate here over time instead of on or around the dune crest. With the exception of the distinctive snout, this dune resembles all the surrounding dunes in this part of the desert and extends south for ~120 km.

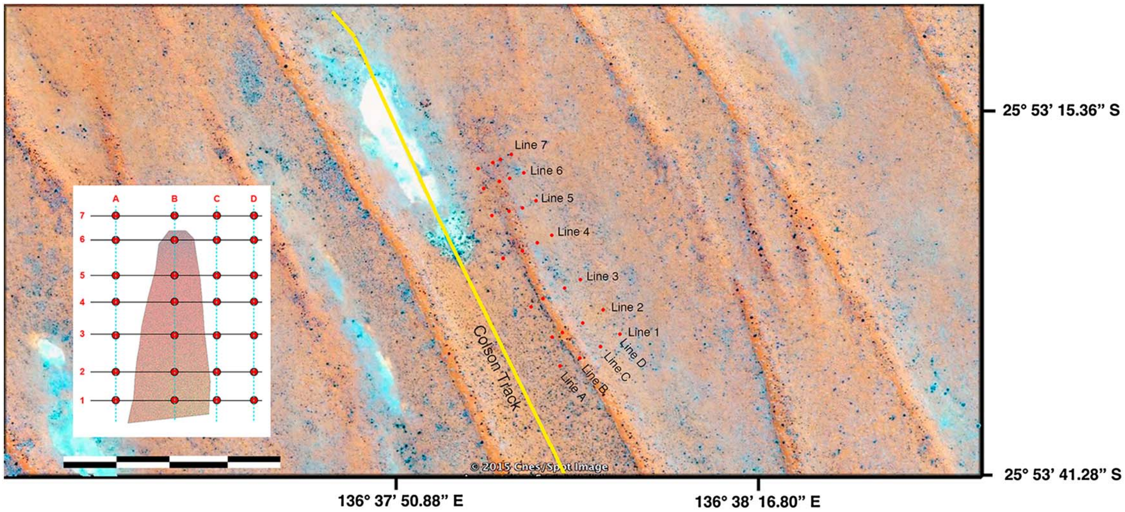

Figure 2. Locations of the survey lines and stakes laid out over the downwind end of a linear dune. The dune is located just east of the Colson Track (yellow line). The stakes were placed in longitudinal and perpendicular lines where each longitudinal line was labeled A, B, C, and D from west to east and each perpendicular line was labeled 1, 2, 3, 4, 5, 6, and 7 from south to north (inset). The scale bar on the main image is 425 m across. Stakes that were unearthed due to deflation were hammered back into the ground to the same initial depth (*image courtesy of CNES/Spot Image*).

To survey and monitor the dune, we placed 28 rebar stakes in a 4 × 7 grid over and around the downwind end of the dune (Figure 2). Each stake was ~60 cm long and hammered into the ground up to about half this length. For convention, the east-west lines were numbered 1–7 from the south to north, and the north-south lines were lettered A–D from the west to the east (Figure 2, insert). In May 2006, July 2008, and June 2014, we measured and recorded the length of each exposed rebar stake, photographed each stake with the dune in the background, and used GPS to survey each numbered and lettered line.

Our GPS measurements were collected with a Trimble R8 GPS system, which consists of two GPS receivers that work in tandem. A base receiver remained fixed on a tripod at a known location during the survey. The base receiver determined its own location with a horizontal accuracy of ±5 mm + 0.5 ppm RMS and a vertical accuracy of ±5 mm + 1 ppm RMS with satellite-based differential correction. The location of the base receiver was then used as the reference point for all the surveys. The other receiver was mounted on a pole 1.8 m in length and was used for the data collection. Communication between the base and roving receivers was maintained with an integrated 450 MHz receiver/transmitter with a typical range of 3–5 km. This allowed for real-time differential correction as we collected points with the roving receiver that had a reported horizontal accuracy of ±10 mm + 1 ppm RMS and a vertical accuracy of ±20 mm + 1 ppm RMS.

During each field season, we conducted GPS surveys along each of the staked lines (Figure 2). Typically, we collected points every 30–50 cm between the stakes. Once these surveys were completed, we collected additional data over the dune and the surrounding swales that were more random and intended to be space filling for constructing digital elevation models (DEMs) that were used to assess changes over the 8 year period.

While funding and time constraints did not allow emplacement of a remote meteorological station, we measured wind velocity profiles for several other dunes in the area. In addition, we have obtained climate data from weather stations surrounding the Simpson Desert. These data were analyzed to determine changes in the wind regime throughout the year and to calculate the net sediment flux for the desert region.

4. Results

4.1. General Observations and Stake Data

Table 1 presents a summary of the total exposed stake lengths recorded during each survey, while Figure 3 presents repeat photographs of the stakes composing line 6 that were taken during the surveys. Even after only 2 years, the July 2008 survey showed that dramatic changes had taken place. In particular, the stakes along the crest of the dune (line B) indicated sand accumulations of ~8 cm to over 30 cm (Table 1). In some

Table 1. Exposed Lengths (cm) of Individual Stakes as a Function of Year[a]

	A	B	C	D	
1	31.0	37.5	29.5	31.8	2006
	31.0	Down	27.0	30.7	2008
	Not found	Not found	Not found	Not found	2014
2	37.0	30.4	37.5	30.7	2006
	46.3	Buried	42.0	31.7	2008
	Not Found	38.7	43.8	33.0	2014
3	28.5	17.5	35.0	30.4	2006
	24.3	Buried	29.5	26.7	2008
	Not Found	31.1	20.3	19.7	2014
4	31.8	25.0	31.0	30.2	2006
	39.0	40.5	36.5	33.0	2008
	34.3	16.5	41.3	36.2	2014
5	30.7	31.7	32.5	25.4	2006
	33.6	Buried	24.0	31.5	2008
	29.2	Not found	Not found	Not found	2014
6	30.3	28.8	38.5	33.6	2006
	Down	38.7	31.0	31.7	2008
	Not found	15.9	32.4	25.4	2014
7	35.4	36.1	35.4	33.5	2006
	35.7	28.0	36.0	33.4	2008
	38.1	17.8	38.1	28.6	2014

[a]For reference, line B runs along the original dune crest. See Figure 2 for the placement of individual stakes. Any stakes that were found down (i.e., unearthed due to deflation) were placed back into the ground. Stakes that were not found may have been buried, hidden in vegetation, or down and not seen.

places, we estimated that over 1 m of sand was deposited on the crest. In contrast, however, stake 1B was lying on the surface, presumably having been unearthed as a result of dune surface deflation. Over the same interval, stake 6B, located on the dune snout, had experienced ~10 cm of deflation.

By the time of the June 2014 survey, most of the stakes located along the dune crest (line B) had reappeared, and stake 6B located at the snout had experienced ~13 cm of accumulation. However, the stake data alone are a bit misleading as it was clear that while new material had been deposited on the crest, the general position of the crest line had also shifted. The stakes located on the basal flanks of the dune (lines A and C) as well as the neighboring swale (line D) had experienced between 2 and 10 cm of accumulation and deflation over time. While deflation generally seemed to be concentrated at the base of the dune after the second survey, over time, there was no obvious or consistent pattern as to where the accumulation and deflation had taken place.

Analysis of the stake data indicates that there is no apparent net accumulation or deflation of sand, particularly in the swales. Instead, it appears that the entire surface in the vicinity of the dune has an active layer of sand that is at least several centimeters thick. The dune crest seems to be particularly active, locally with upwards of tens of centimeters of material being reworked between surveys.

4.2. GPS Measurements

The GPS surveys show that dramatic changes took place along the crest of the dune, locally with a meter or more of sand accumulating between surveys, only to be deflated in subsequent years (e.g., lines 2 and 3 in Figure 4). Visual field observations also suggested that the crest and upper flanks of the dune locally had shifted slightly east or west (e.g., lines 2 and 3 in Figure 4), implying a small component of lateral migration. Future GPS surveys will be needed to document these finer-scale changes in more detail.

Line 7 (Figure 4) was established just north of the dune snout. The gradual change in elevation to the east reflects a topographic rise resulting from sand that had accumulated in the adjacent swale near a neighboring dune. Overall, these GPS data reveal centimeter-scale changes in the local topography and do not indicate large-scale, net changes in the elevation of the dune or surrounding surfaces.

Line B in Figure 4 is the survey along the dune crest. If the linear dunes in the Simpson Desert were forming mainly as a result of linear extension [*Twidale and Wopfner*, 1990], then we would expect the stake and GPS survey data to reveal evidence for northward advance of the dune snout. Although the stake data (stakes 6B

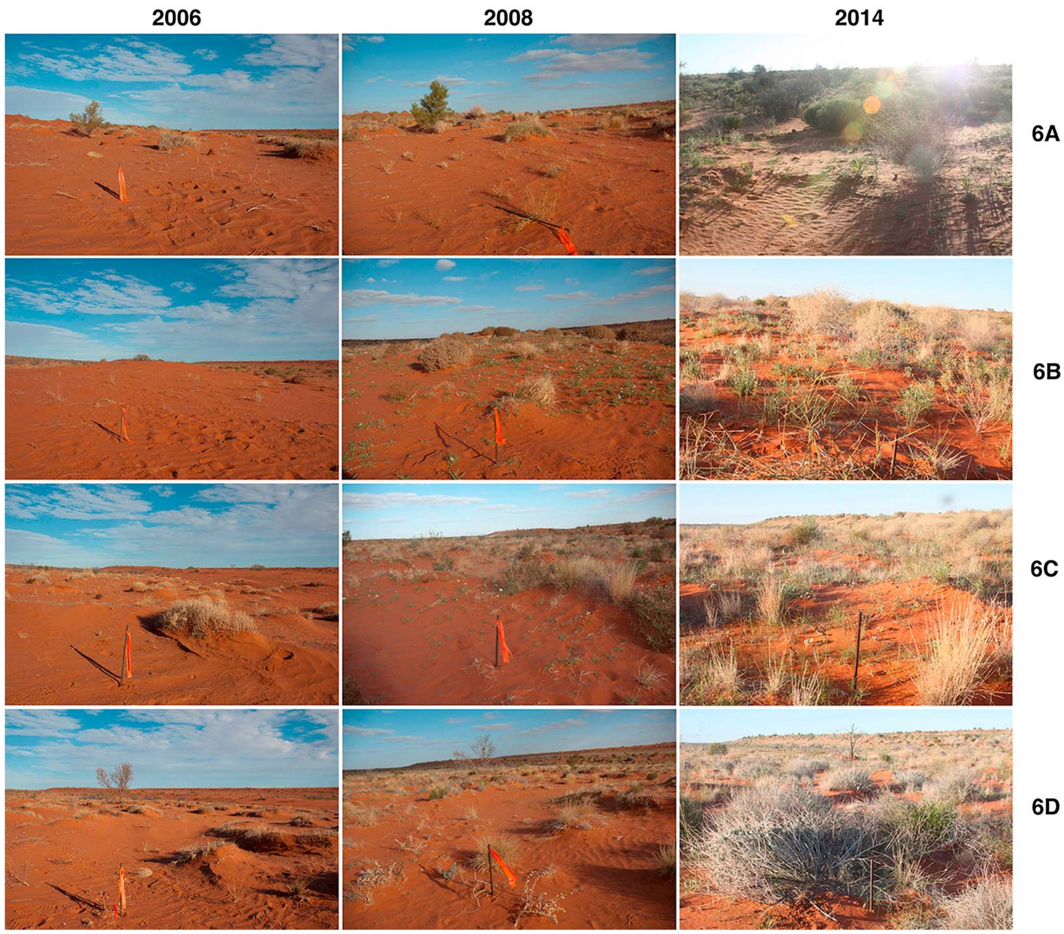

Figure 3. On each field campaign, we measured the height of the stake above the sand surface and attempted to photograph it in the same way we had originally done in 2006. These series of photographs show the changes observed for the stakes along line 6 (see Figure 2 for context). The vegetation changed dramatically after 2006, suggesting that the area surrounding the dune had been subjected to a drought or bush fire sometime before we began our survey. Note that in 2008 stake 6A had fallen to the ground because of deflation. The stake was hammered back into the ground to the same initial depth, and by 2014, the same stake was completely buried. On average, our surveys show that several centimeters of sand move across the dune and surrounding desert each year, with morphological changes being more dramatic on the dune crest and upper flanks.

and 7B in Table 1) and GPS measurements indicate that several centimeters of sand fluctuations occurred at the snout, similar in magnitude to the surrounding swales, there was no significant or systematic change in the shape or position of the snout over the course of our surveys.

4.3. Digital Elevation Models

Using the GPS survey data together with additional points collected on and around the dune, we constructed a series of digital elevation models (DEMs) using a kriging algorithm in Golden Software's Surfer program (Figure 5). The height accuracy of the DEM is the same as the GPS survey (~1 cm). The horizontal accuracy is ~1 m due to our point spacing, which is admittedly crude. The top three DEMs shown in Figure 5 are from each year the surveys took place (vertical scale in meters). In general, these DEMs by themselves do not show many changes in the overall morphology of the dune. However, by subtracting one DEM from another in Surfer, subtle changes in the morphology of the dune and surrounding area can be seen. These differences are shown at the bottom of Figure 5 (scale in centimeters). In each subsequent survey, sand was preferentially deposited on the dune, particularly on and around the crest, and overall, the dune appears to have accumulated several centimeters of sand. This suggests that the dunes are accreting vertically [cf. *King*, 1960; *Hollands*

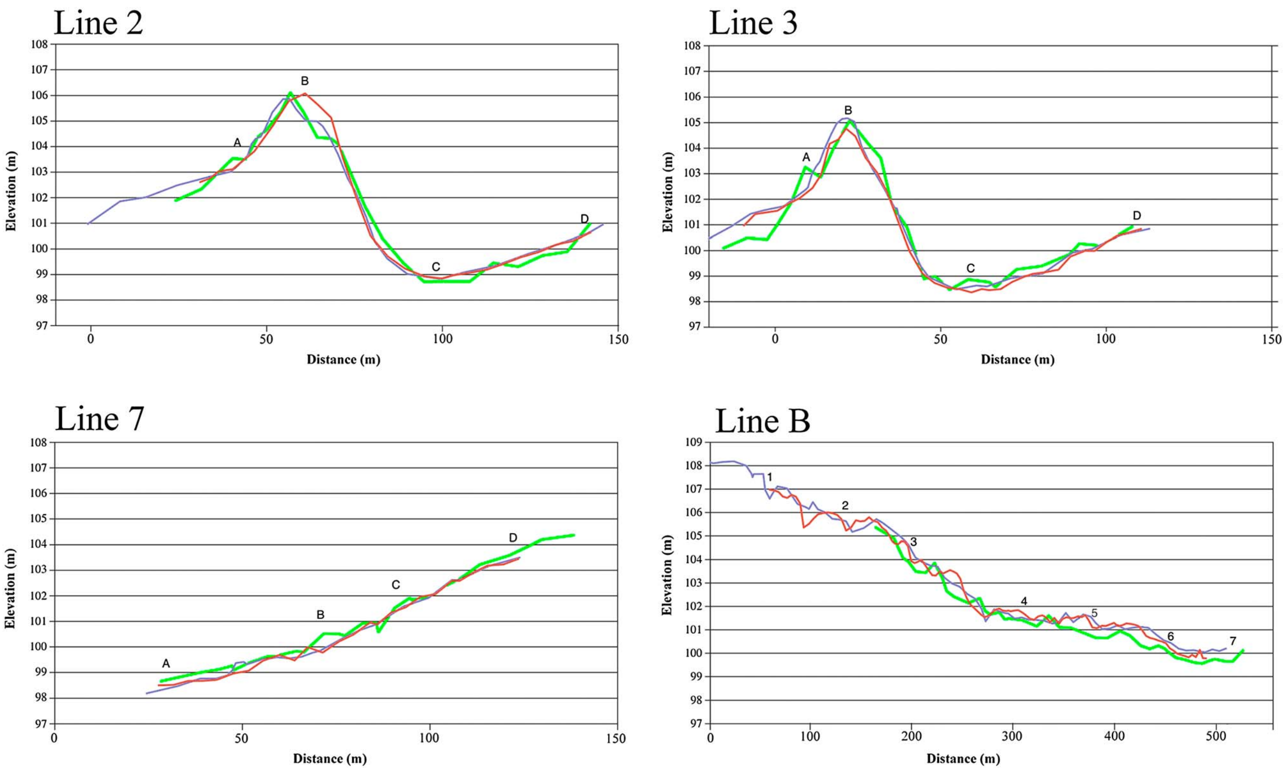

Figure 4. GPS profiles of several stake lines measured in 2006 (red), 2008 (blue), and 2014 (green). Individual stakes are represented by letters and numbers (see Figure 2). Note that in the perpendicular surveys taken across the dune (represented by lines 2 and 3) the height of the dune surface changed dramatically, locally by 1–2 m. However, the area in front of the dune snout (represented by line 7 and the downwind part of B) changed only minimally.

et al., 2006; *Bristow et al*., 2007a]. The DEMs also show that the local swales are both accumulating and deflating without any distinguishable pattern, which is consistent with our other observations.

4.4. Wind Environment

Through the Australian Government's Bureau of Meteorology, a variety of climate data are available online for different weather stations surrounding the Simpson Desert, and some of these data date back several decades (Table 2). In particular, the Bureau of Meteorology has plotted rose diagrams of wind direction versus wind speed using monthly and yearly averages. The wind roses provided by the Bureau of Meteorology summarize the winds at a particular location and show their strength (wind speed km/h), direction, and frequency (expressed as a percentage of total time) at both 9:00 A.M. and 3:00 P.M. (Figure 6). The percentage of time calm conditions (no wind) were recorded is represented by the size of the center circle, and the annual percentages of calm winds observed at each of the locations are listed in Table 2. North is to the top of the diagrams, and eight directions are used. The branches are divided into segments of different colors, which represent the wind speed binned by 10 km/h increments. The length of any particular branch represents the percentage of time winds were recorded from any particular direction. *Bagnold* [1941] showed that threshold wind speeds to initiate sediment transport range from 0.2 to 0.4 m/s, or 0.72 to 1.44 km/h. Because the wind data were plotted in 10 km/h bins, we assumed the threshold velocity for sand movement was anything above calm conditions; however, it is likely that winds in the 0 to 10 km/h range were often below threshold. We estimated the net sediment flux by conducting a vector analysis of magnitude (i.e., frequency) and direction of the wind speeds above calm conditions (Figure 6). Because the winds are expressed as direction and a percentage of time they blew from any particular direction, the resulting sediment fluxes are also presented as a direction while their magnitudes are expressed as a percentage. Thus, the sediment flux is not a quantitative term (i.e., m^2/yr). Rather, our calculated sediment fluxes are relative to all the winds at a particular location. Note also that the branches of the rose diagrams (Figure 6) show winds blowing into the center of the diagram, while the sediment flux is shown as an arrow blowing out of the diagram.

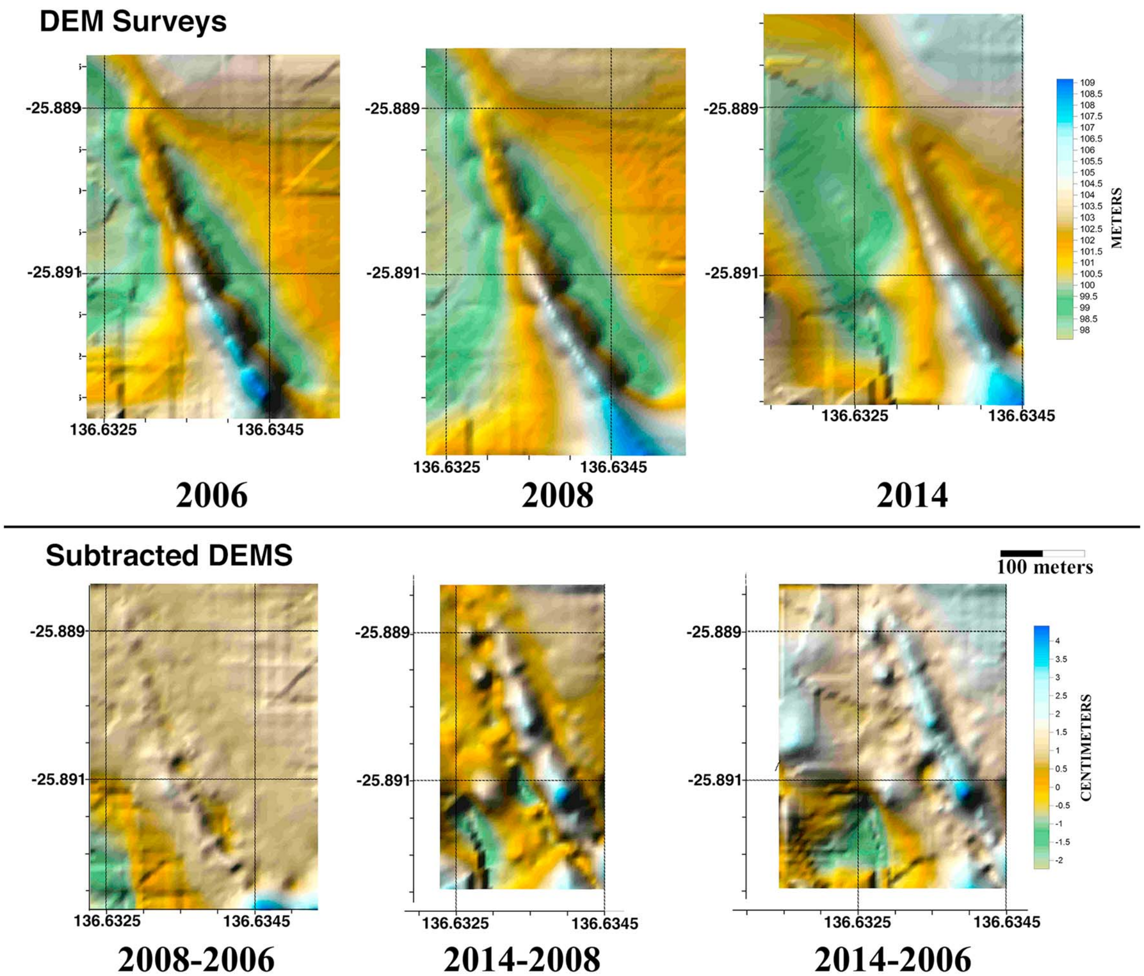

Figure 5. A series of digital elevation models (DEMs) constructed from GPS survey data. The height accuracies of the DEMs are ~1 cm, and the horizontal accuracies are ~3 m. The top DEMs were produced by the GPS surveys during each field season. The bottom DEMs were produced by subtracting one DEM from the other as captioned. Note that the vertical scale of the top three DEMs is in meters, while the scale of the bottom three DEMs is in centimeters. The spacing between latitudinal and longitudinal tick marks is 0.0005°. Because the GPS surveys did not always cover the same area surrounding the dune, key latitudes and longitudes are marked for reference to help with comparing one DEM with another. It can be seen that sand is preferentially being deposited on the dune, and overall, the dune appears to be aggrading centimeters of material. Meanwhile, the local swales appear to be both aggrading and deflating over time.

Fryberger [1979] also discussed the wind environment of the Simpson Desert based on identical climate data from Oodnadatta and observed that there is a "wide unimodal distribution of effective winds" that is dominated by winds from the south. However, weather data that have been added by the Bureau of Meteorology subsequent to *Fryberger's* [1979] study indicate that the effective winds are actually from the southeast (Table 3 and Figure 6). The difference in effective wind direction does not necessarily imply that there has been a change in the wind regime over time. Instead, our study benefits from almost four decades of additional data, which are about twice the amount available at the time of *Fryberger's* [1979] study.

Table 2. Details of the Rose Diagrams Showing Wind Direction Versus Wind Speed Presented in Figure 6

	Latitude	Longitude	Elevation (m)	Calm	Total Observations	Observation Range
Marla Police Station	27.3002°S	133.6201°E	323	12%	8,303	09 Aug 1985 to 30 Sep 2010
Birdsville Airport	25.8975°S	139.3472°E	46	2%	3,652	29 Jun 2000 to 30 Sep 2010
Kulgera	25.8428°S	133.3027°E	508	3%	10,440	24 Sep 1980 to 30 Sep 2010
Ringwood	23.8289°S	134.9555°E	416	11%	5,430	01 Jan 1965 to 31 Aug 1981
Oodnadatta Airport	27.5553°S	135.4456°E	116	15%	17,009	07 Nov 1942 to 30 Sep 2010

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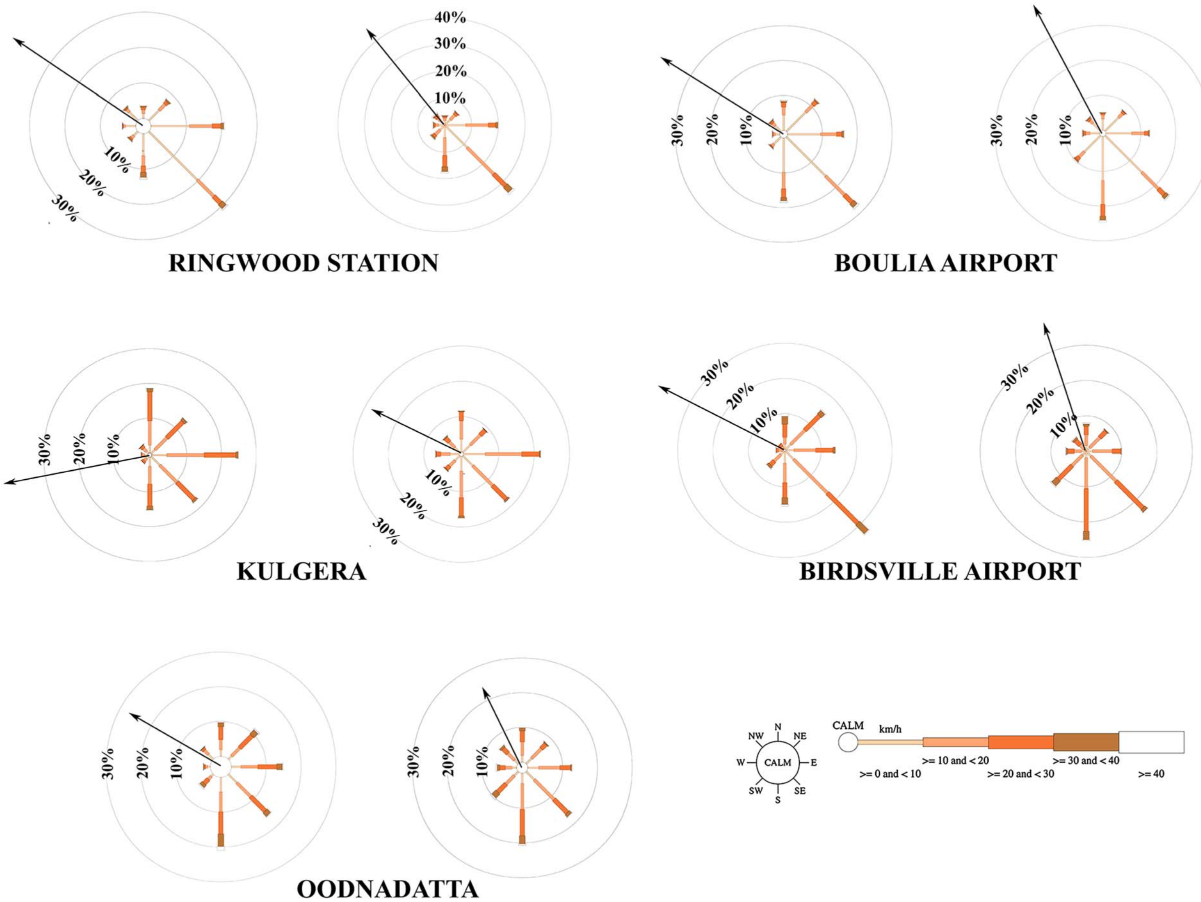

Figure 6. Wind data recorded from weather stations surrounding the Simpson Desert. In each case, the left rose diagram represents average 9:00 A.M. wind directions and the right rose diagram represents 3:00 P.M. wind directions. The vanes are plotted from 0 to 10, 10 to 20, 20 to 30, and 30 to 40 km/h. Typically, the wind speeds are measured 10 m above the ground and averaged over 10 min before the observations are recorded. The circles represent the percentage of time each observation was observed and are plotted at 10% intervals. Arrows represent the net direction of sediment flux (resultant drift direction) for each diagram. Note that there is currently a strong NW to NNW direction to the sediment flux for most areas of the Simpson Desert and surroundings (*rose diagrams modified from data available from the Australian Government's Bureau of Meteorology*).

The monthly changes observed in wind speeds and directions are typified by the data collected at Oodnadatta (Table 3). In general, there is a slight seasonal shift in the effective winds during the Southern Hemisphere winter months. Beginning in May and lasting until August, the effective winds begin to come from westerly directions, but these are often weak relative to the other monthly winds. *Fryberger* [1979]

Table 3. Oodnadatta Monthly Sediment Flux

Month	9 A.M. Direction	9 A.M. Magnitude	3 P.M. Direction	3 P.M. Magnitude
January	N300W	45%	N327W	41%
February	N302W	47%	N315W	48%
March	N307W	46%	N319W	44%
April	N303W	40%	N324W	37%
May	N322W	22%	N317W	22%
June	N352W	6%	N322W	13%
July	S92E	4%	N358W	8%
August	N300W	9%	S91E	5%
September	N286W	23%	N54E	6%
October	N282W	35%	N354W	16%
November	N286W	37%	N334W	24%
December	N297W	43%	N336W	33%
Annual Flux	N300W	28%	N324W	26%

Table 4. Summary of Measured Sediment Fluxes for Weather Stations Surrounding the Simpson Desert

Location	9 A.M. Direction	9 A.M. Magnitude	3 P.M. Direction	3 P.M. Magnitude
Birdsville Airport	N297W	46%	N342W	37%
Boulia Airport	N302W	40%	N332W	41%
Ringwood Station	N304W	43%	N321W	44%
Kulgera	N269W	42%	N296W	28%
Oodnadatta Airport	N300W	28%	N324W	26%

suggests that this results in a "gradual swing of the resultant drift direction" from the northwest in January to the east-northeast in July and back again, essentially arguing that the winds in the Simpson are bimodal. However, the Bureau of Meteorology data indicate that this is only true in July and August, it is only is only true for part of the day, and the winds are infrequent (Figure 6 and Table 3). For instance, Table 3 shows that, in July, the 9 A.M. sediment flux direction is weak (4% magnitude) and toward the east (S92E), but by 3 P.M. the sediment flux direction shifts back toward the north (N358W). In August, the sediment flux directions switches between the morning and afternoon. At 9 A.M., the sediment flux direction is weak (9% magnitude) toward the northwest (N300W), but by 3 P.M., the afternoon sediment flux direction shifts back toward the east (S91E). There is a wide unimodal distribution of effective winds at Oodnadatta as *Fryberger* [1979] argues. Overall, however, winds that blow from directions other than the south-southeast are short lived, infrequent, and often weak, resulting in a sediment flux direction that is toward the north-northwest. This is true of Oodnadatta Airport data as well as the other weather stations that surround the Simpson Desert, as can be seen in the rose diagrams presented in Figure 6 and the sediment flux data presented in Table 4.

Even wide unimodal winds make it difficult to form and maintain the Simpson dunes by the linear extension model, which requires bimodal winds to move and concentrate sand toward the front of the dune [e.g., *Twidale and Wopfner*, 1990]. Instead, our observations support the vertical accretion/lateral migration models [*Hollands et al*., 2006; *Bristow et al*., 2007a], in which unimodal winds move the bulk of sand toward the northwest. Obviously, our observations were made over 8 years, and we did not witness the initial formation of the dune. However, our observations do indicate that the dune is currently being maintained, if not growing, by vertical accretion, and that no detectable linear extension appears to be taking place. If climatic conditions were much different when they originally formed, the linear dunes would now be relict features and some other dune form would superpose them, but that is not the case. The Simpson linear dunes may be a result of the deep abundance of sand while reflecting a broadly consistent overall wind regime that may date back several tens of thousands or possibly a million years or more based on the ages of some of the dunes [*Nanson et al*., 1992; *Fujioka et al*., 2009; *Fujioka and Chappell*, 2011].

5. Discussion

Our observations have important implications both for understanding linear dunes on the Earth and for interpreting the environmental conditions on other planets, particularly Titan.

5.1. Terrestrial Implications

On Earth, dune morphology is often controlled by the presence of vegetation [e.g., *Lancaster*, 1995]. The fact that linear dunes in Australia can be heavily vegetated led *Tsoar* [1989] to the interpretation that they are inactive and are an entirely different feature separable from seif dunes. While it is inarguable that the vegetation in the Simpson Desert provides some control over sediment movement, our observations suggest that this control is limited. Our dune surveys show that centimeters of sand are reworked over any single spot within a few years regardless of the presence of vegetation. More broadly, this may suggest that there is an active layer of sand several centimeters thick across much of the Simpson Desert.

Another important observation is shown in Figure 3. In each subsequent survey, it can be seen that the overall amount of vegetation increased on the dune over time: during the initial survey in 2006, the dune was sparsely vegetated, but by 2014, it was more heavily vegetated. This is most likely part of the natural desert vegetation cycle that is controlled primarily by rainfall and bushfires. As a result of global warming, the climate of the interior of Australia has become more arid (Ausralian Government, Bureau of Meteorology, Annual Climate Statement, 2013, http://www.bom.gov.au/climate/current/annual/aus/2013/) and bushfires are becoming more frequent [*Bryant*, 2009]. In 2011, for example, it was widely reported that a bushfire consumed vegetation of over five million hectares (~20,000 square miles) in the Simpson Desert. Although the total area burned varies considerably from year to year, *Bryant* [2009] estimates that a majority of land in the southern Northern Territory, which includes part of the Simpson Desert, has burned at least once over the last 5 years. It is possible that we began our survey following a drought or bushfire that degraded the vegetation on our dune and that the vegetation has slowly recovered between subsequent surveys. The important point is that while there is typically some amount of vegetation present on the linear dunes in the Simpson Desert, the presence of this vegetation is insufficient to prevent movement of sand on and around the dunes.

To investigate the potential influence of vegetation cover on sediment mobility by the wind, we wanted to determine typical values of the roughness height, or z_0, on dunes and swales with variable amounts of vegetation. The roughness height is the height above the surface where the wind speed becomes zero. To determine this parameter, we measured wind velocity profiles (at locations different from the surveyed dune) using three SPER Scientific anemometers that recorded maximum, minimum, and average wind speeds (0.1 m/s accuracy, ±2% precision) during a time interval determined by the manual start and stop times of the recording period. The three anemometers were logarithmically spaced in height above the surface between roughly 10 cm and 1.60 m, measured to the center of the spinning vane used for each sampling head. The anemometers were affixed to a thin portable pole that was faced into the wind prior to each recording session. The upwind surface at each tower location was consistent over a fetch of $>$200 m at each site. A logarithmic least squares fit was applied to the wind profile data from each run; the fit was done for an expression of the form $y = a + b \ln x$, where y is the observed wind speed at height x. Setting $y = 0$ in the best fit expression is then solved to give $z = z_0$. With z_0 and the wind speed at one height, the wind speed at any other height is obtained from the Prandtl-von Kármán logarithmic relationship [e.g., *Prandtl*, 1935; *Schlichting*, 1955; *Walker and Nickling*, 2002], also known as the "Law of the Wall":

$$U(z) = (u^*/k)\ln(z/z_0) \quad (1)$$

where U is the wind velocity at height z, u^* is the friction speed, κ is the von Kármán constant (typically 0.41), and z_0 is roughness height.

Using z_0 and the observed wind speed measured at each altitude, the Law of the Wall then gives the corresponding shear velocity for each anemometer height. The resulting shear velocities (averaged over the three anemometers) for the recording sessions ranged from 0.13 to 0.59 m/s. Values of u^* obtained by others range from 0.2 m/s (for well-sorted fine sand) to about 0.4 m/s (measurements in diverse desert settings) at the threshold of sand motion [*Bagnold*, 1941; *Greeley and Iversen*, 1985; *Nickling*, 1988; *Lancaster and Baas*, 1998; *Svasek and Terwindt*, 1974; *Creyssels et al*., 2009; *Kok et al*., 2012], although measured threshold shear velocities as high as 0.8 m/s have been observed at sites where vegetation is densely intermixed with sand [*Lancaster and Baas*, 1998]. We conclude that much of the time during our profiling sessions, the wind should have been above threshold, yet little or no sand was observed to move during any of the wind profile runs.

Roughness heights obtained from our wind measurements ranged from 0.03 to 0.07 m, which is roughly one tenth the height of the endemic vegetation, including common grass species such as *Zygochloa paradoxa* and *Triodia*. These values were consistent whether they were measured on the dunes or in the swales. Our measurements of roughness heights indicate that it will be difficult to mobilize large volumes of sand under "normal" vegetation cover conditions. Certainly, wind gusts and turbulence near the vegetation allow localized zones downwind of the large plants to experience wind scour, but the roughness height associated with the vegetation will severely restrict how much sand can be mobilized over a broad region. However, when the relatively frequent brush fires locally clear out the vegetation cover, the wind then has a much greater potential to mobilize sand within the burn zones; the vegetation no longer causes the height of zero wind velocity to occur well above the sand surface. This interpretation is consistent with our field observations of increasing vegetation cover at the surveyed dune during the study period, likely illustrating vegetation recovery following an earlier burn event.

Although our measurements were only made over a short period, the other important observation from our study is that while the dune appears to be vertically accreting sand, at present, it does not appear to be extending linearly any significant distance. In a similar study, *Telfer* [2011] determined the depositional history of a linear dune with a "prominent termination" (i.e., snout) located in the southwestern Kalahari.

He obtained optically stimulated luminescence (OSL) age dates for 42 samples that were collected at depth along a ~600 m traverse that also included the dune's snout. He found evidence for foreset beds at the dune's snout, and OSL age dates indicated several punctuated events during the late Pleistocene and early Holocene when the dune extended linearly. In contrast, the samples collected along the dune crest included some younger ages (<20,000 years to the present), suggesting that this part of the dune has been reworked by seasonal variations in the location of the crest. *Telfer's* [2011] samples were collected at 1 m intervals and, combined with the limited resolution of the OSL age, are insufficient to determine how much (if any) accumulation may be occurring today. However, his observations suggest that potentially the linear dune we analyzed in the Simpson Desert is also being "reworked." It is an interesting possibility that could be tested by future surveys and luminescence dating. Given the great ages of many of the Simpson linear dunes and the fact that rainfall would gradually erode them [*McFarlane et al*., 2005], there must be some process that is actively maintaining them. Our observations suggest that this process is vertical accretion.

In other parts of the Simpson, ground-penetrating radar measurements [*Hollands et al*., 2006; *Bristow et al*., 2007a] show that some linear dunes may have shifted slightly eastward from their clay-rich cores, but this is commonly much less significant in comparison to the overall vertical accretion of dunes. Over the short period that we monitored our dune, widespread lateral movement was not detectable (Figure 4).

5.2. Implications for Titan

The presence of linear dunes on Titan implies that surface conditions are dry [*Lancaster*, 2006], that there is abundant sand-sized material that is most likely organics derived from atmospheric processing of methane into longer-chain molecules [*Soderblom et al*., 2007], and that there are surface winds strong enough to initiate particle movement [*Lorenz et al*., 2006; *Radebaugh et al*., 2010]. The fact that there are dune forms on Titan indicative of active aeolian processes is surprising considering the distance of Saturn and Titan from the sun, which limits the amount of energy from solar insolation for driving surface winds [*Lorenz et al*., 2006]. Instead, it appears that the tidal pull from Saturn, in addition to the insolation on the atmosphere, is sufficient to drive surface winds on Titan [*Tokano and Neubauer*, 2002]. However, by most interpretations, the perceived eastward orientation of the linear dunes on Titan [*Lorenz and Radebaugh*, 2009] requires westerly surface winds, which are difficult to explain from general circulation models [*Tokano*, 2008, 2010]. A variety of wind regimes have been proposed, including unimodal, acute bimodal, and obtuse bimodal as summarized by *Tokano* [2010]. Many of the proposed unimodal models [*Lorenz et al*., 2006; *Radebaugh et al*., 2008; *Rubin and Hesp*, 2009] suggest that the winds are in a direction parallel to the dune orientation. However, *Rubin and Hesp* [2009] allow for the possibility that winds are oblique to the dune orientation, which is also supported by *Tokano's* [2008, 2010] general circulation model that predicts unequal wind modes at some locations, generating resultant drift directions that are oblique or transverse to the orientation of the dunes. Such wind regimes are certainly supported by our observations in the Simpson Desert.

It is also interesting to note that linear dunes are frequently found on ergs of considerable thickness. The sand in the central Simpson Desert is 10–35 m thick [*Wopfner and Twidale*, 1967], similar to the sand thickness in the Namib Desert where linear dunes are also found [*Lancaster*, 1988]. The possibility that the linear dunes on Titan reflect an "ample sediment supply" has previously been reported [*Lorenz et al*., 2006]. However, it has not been generally appreciated that the ergs on Titan (and potentially Mars and Venus) may be several times thicker than the height of the observed linear dunes, and the volume of sediment they represent implies a dramatic climatic shift from fluvial depositional to aeolian processes [*Lorenz et al*., 2006] or extensive accumulation of hydrocarbon particulates generated by photochemistry over time [*Wahlund et al*., 2009; *Yung et al*., 1984].

6. Summary

We have presented 8 years of temporal observations and measurements of a linear dune located in the Simpson Desert of central Australia. Our results show that centimeters of sand are transported on and around the dune annually, a finding that may apply more widely across the Simpson Desert. Accumulations of sand on the dune crest and upper flanks between surveys were often dramatic and exceeded a meter in some instances. Climate data indicate that winds in the Simpson Desert are widely unimodal with a net sediment flux toward the northwest and north-northwest, locally oblique to the dune orientation. Our results indicate that the linear dunes in the Simpson Desert are active, which is contrary to some suggestions that they are inactive simply because they are vegetated [e.g., *Tsoar*, 1989]. Our observations suggest that linear dunes are actively maintained if not growing primarily by vertical accretion and that the sand is derived locally [cf. *King*, 1960; *Pell et al.*, 1999, 2000]. Appreciable linear extension was not observed during the period of monitoring, and while our observations cannot rule out a potential lateral migration component to the dune's dynamics [cf. *Bristow et al.*, 2007a; *Hollands et al.*, 2006], no appreciable lateral changes in the dune's middle and lower flanks were observed. The implications from our observations are that linear dunes on other planetary surfaces could form in wind regimes that are unimodal or widely unimodal and locally oblique to dune orientation, and where the underlying sand sheet probably extends to considerable depths. Our observations provide a modern Earth analog that may support interpretations of global circulation models for Titan's atmosphere as presented by *Tokano* [2008, 2010] where linear dunes are able to develop with orientations that are oblique or transverse to the effective winds and resultant drift direction.

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